

ROTATION CURVES OF 967 SPIRAL GALAXIES: IMPLICATIONS FOR DARK MATTER

MASSIMO PERSIC, PAOLO SALUCCI & FULVIO STEL
SISSA, Via Beirut 4, 34013 Trieste, Italy

ABSTRACT

We present the rotation curves of 967 spiral galaxies, obtained by deprojecting and folding the raw $H\alpha$ data published by Mathewson et al.(1992). Of these, 80 meet objective excellence criteria and are suitable for individual detailed mass modelling, while 820 are suitable for statistical studies. A preliminary analysis of their properties confirms that rotation curves are a universal function of luminosity and that the dark matter fraction in spirals increases with decreasing luminosity.

1. Introduction

Rotation curves (hereafter RCs) are the prime mass tracers within spiral galaxies. Therefore, knowledge of their morphology and structural implications is essential for theories/experiments concerning galaxy formation (e.g.: Cen & Ostriker 1993; Navarro & White 1994; Evrard et al.1994). Such a knowledge is of course crucially increased when large samples of good-quality curves become available.

The $H\alpha$ velocities referred to the plane of the sky, of nearly one thousand spirals published by Mathewson et al.(1992; hereafter MFB) represent by far the largest available sample of (raw) measurements of galaxy rotation. However, it is well known that recessional velocities, which are adequate for the purpose of estimating the maximum circular velocity, require a careful treatment before they can yield the actual rotation curves. In a related paper (Persic & Salucci 1995; hereafter PS95), after folding, deprojecting and smoothing the raw MFB data we work out the actual RC's. Because of its size, homogeneity, quality, and spanned range of luminosities and asymptotic velocities, the sample of RCs thus obtained will serve as a main database for studies of galaxy structure.

The plan of this contribution is as follows. In section 2 we outline the procedure used to obtain the RCs from the raw data. In section 3 we classify the 967 RCs into three quality subsets. Section 4 briefly illustrates the results of a preliminary analysis of these RCs. The 967 rotation curves will be published in Persic and Salucci, 1995 (PS95).

2. Data Analysis

For details of the observations and data acquisition and reduction, the reader is referred to MFB. Here we outline the basic procedure leading to the final RCs. For each RC it includes: 1) a selection of the individual velocity data; and 2) the identification of the kinematical center about which to fold such data. In addition, step 3) in order to evaluate the extension of each RC, we have compared the radius corre-

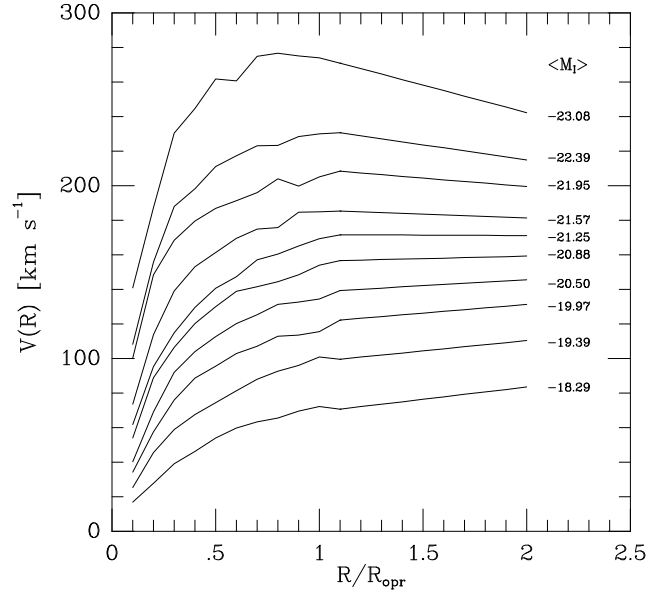


Figure 1: Synthetic rotation curves resulting from the coaddition of the 616 RC's from PS95. Galactocentric radii are normalized to the optical radius

sponding to the farthest measured velocity with the optical size R_{opt} . 1) The quality of each velocity point is measured by the cross-correlation coefficient ρ (given in the public MFB data files) between the observed and template H α line profiles. Based on the rms velocity error as a function of ρ , we have found that a good correlation ($\rho > 0.35$) is essential in order to ensure a high reliability of the measure.

2) The photometric center (the point of maximum emission in the I -band) does not necessarily coincide with the dynamical center of the galaxy. To obtain the kinematical center we have proceeded as follows: we have assumed that, once folded, each curve must be perfectly symmetric around its kinematical center, so that the curve defined by the approaching side coincides (within errors) with the one traced by the receding side. In practice, we have started from the photometric center; then, if warranted, we have estimated the kinematic center by folding the data around slightly different zero-points until the global symmetry of the velocity arms is maximized. Table 1 of PS95 contains the solution of this folding procedure, i.e.: the heliocentric systemic velocity, and the offset of the kinematic center from the photometric center.

3) It is essential to have a reference scale for the optical size of each galaxy in order to assess the extension of the RC as compared with the visible matter. For this purpose, using the I -band CCD surface photometry of MFB, we have computed the radius, R_{opt} , encompassing 83% of the integrated light (see Table 1 of PS95; for an exponential disk this corresponds to 3.2 lengthscales, which in turn corresponds, for a Freeman disk, to the de Vaucouleurs 25 B -mag/arcsec² photometric radius.)

3. The Rotation Curves

We have identified 900 RCs that are symmetric, with reasonably low rms internal scatter and reasonable high sampling density. These curves are shown in Fig.1 of

PS95. This set of 900 safe RCs can be split into a subset of 80 *excellent* curves (Set A), and one of 820 *fair* curves (Set B). The 80 RCs in Set A have the following properties, which ensure that they are good tracers of the gravitational potential in the region of interest and hence are well suited for detailed mass modelling: 1) the approaching and receding sides are very symmetric; 2) the data are extended out to (at least) R_{opt} ; and 3) there are ≥ 30 data points homogeneously distributed with radius and per arm. For each galaxy, from the folded RC we produce a smooth RC as follows. We smooth the folded velocities by binning the $\leq N$ nearest data points contained within a fixed maximum bin size W . The values used for W are mostly $0.050 R_{opt}$ and $0.075 R_{opt}$, and for N are mostly 4 and 6. These values are chosen for each RC according to its sampling density: however, the profiles of the RCs are not significantly changed with other (reasonable) choices as can be seen by comparing the smoothed RCs with the original folded ones. In each bin we compute the average rotation velocity and its uncertainty. The resulting smoothed curves are shown in Fig.2 of PS95. The 820 RCs in Set B fail, to various extents, at least one of the criteria stated above and therefore may be not suitable for accurate and direct mass modelling. However, they constitute a large database for those methods able to recover the DM properties with less stringent requirements on the RC quality.

Finally, the 67 RCs of Set C have severe global asymmetries, large rms internal scatter, insufficient sampling and/or large-scale deviations from circular motion. These curves may be useful for studying the non-axisymmetric disturbances (e.g., bars, spiral arms) in spiral galaxies and are shown in Fig.3 of PS95.

4. Discussion.

For size, homogeneity, and intrinsic quality of the individual curves, the sample of 967 RCs of PS95 constitutes by far the best sample of RCs available to date. As such, it offers a unique opportunity for investigating in considerable depth the properties of dark matter in galaxies, e.g. its radial distribution, the total quantity, and the scaling laws of the structural parameters (see review by Ashman 1992). As part of a preliminary study (Persic, Salucci & Stel 1995), we have co-added the 616 RCs (out of the 900) whose extension exceeds $0.8 R_{opt}$, to form 10 synthetic curves (see Rubin et al. 1985), each related to a different range of luminosity (spanning approximately 5 magnitudes overall) and extending out to $1.6 R_{opt}$ (see Fig.1).

We find that the RCs are well represented by a double straight line, with the change of slope occurring at about R_{opt} (see Fig.1). In detail, RCs depend on radius and galaxy luminosity according to:

$$V(r) = V(R_{opt}) \left[1 + \left(0.30 - 0.27 \log \frac{L_I}{10^{10} L_\odot} \right) \left(\frac{r}{R_{opt}} - 1 \right) \right] \quad \dots 0.4 \leq r/R_{opt} \leq 1.0 \quad (1)$$

$$V(r) = V(R_{opt}) \left[1 + \left(0.12 - 0.16 \log \frac{L_I}{10^{10} L_\odot} \right) \left(\frac{r}{R_{opt}} - 1 \right) \right] \quad \dots 1.0 \leq r/R_{opt} \leq 1.6 \quad (2)$$

where $V(R_{opt}) = 100 (L_I/10^{10} L_\odot)^{0.34} \text{ km s}^{-1}$. We definitely confirm the strong luminosity dependence of the RC shape claimed by Rubin et al. (1985) and supported by Persic & Salucci (1991) and Casertano & van Gorkom (1991).

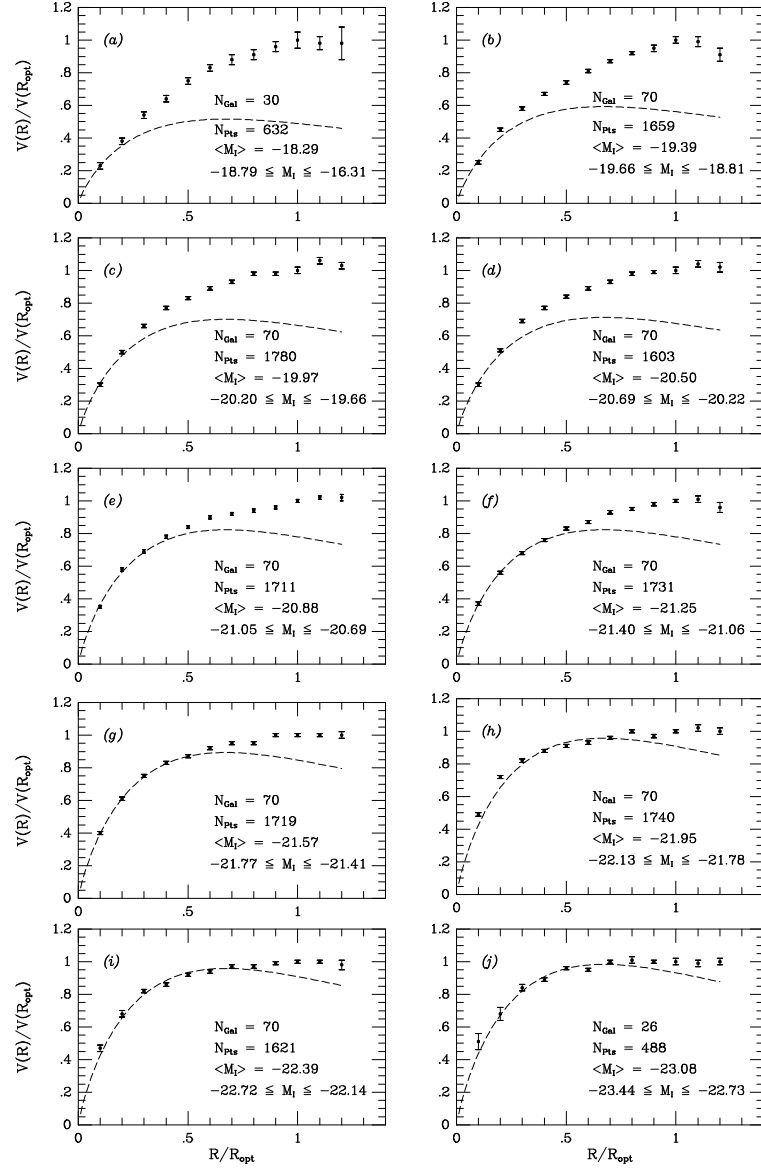


Figure 2: Maximum disk mass-modelling (dashed lines) of the synthetic rotation curves

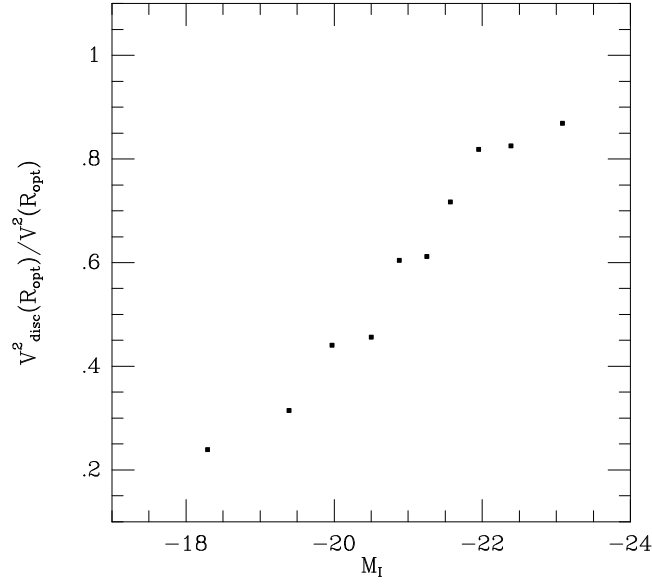


Figure 3: Disk-to-total velocity (mass) ratio as a function of I-Magnitude

We have tried to reproduce the rotation curves with only the luminous matter, assumed as an exponential thin disk. In Figure (2) we plot the contributions of the visible matter (dash lines) alongside the coadded rotation curves of spirals of different luminosity. We note that at about R_{opt} the former is always unable to reproduce the observed kinematics. Moreover, while in high-luminosity galaxies, the stellar disk reproduces the RC inside $r \simeq \frac{2}{3}R_{\text{opt}}$ extremely well, in low-luminosity ones it is unable to do so at any radius. Thus, we find that the dark component is ubiquitous in spirals and that the dark matter fraction inside R_{opt} increases with decreasing luminosity as $\frac{V_{\text{disk}}^2}{V^2}|_{R_{\text{opt}}} \simeq 0.2 + 0.13(M_I + 23)$, in agreement with previous results (e.g.: Persic & Salucci 1988, 1990; Salucci & Frenk 1989; Salucci et al. 1991; Casertano & van Gorkom 1991; Broeils 1992). (For a more detailed mass modelling of spirals see Persic, Salucci, Stel, 1996). In order to study the DM distribution we have calculated the virial radius R_V of the dark halos associated to the various RCs, and have rescaled each curve according to its R_V . Averaging the halo overdensity with a top-hat window $\langle \rho_H \rangle > \frac{4}{3}\pi R_V^3 = 200 \cdot \rho_c$ (where ρ_c is the critical density), we obtain R_V (see Fall & Efstathiou 1980)

$$\frac{3}{4\pi G R_V} \left[\frac{V^2(R_V)}{R_V} - \frac{M_D}{R_D^2} Gx [I_0 K_0 - I_1 K_1]_x \right] = 200 \rho_c \quad (3)$$

where R_D and M_D are respectively the scale-length and the total mass of the galactic disks, while I_0 , I_1 , K_0 and K_1 are the modified Bessel functions calculated at $x = \frac{R_V}{2R_D}$. In this way we can see (Fig. 5) that RCs associated with low luminosity spirals are similar to the inner parts of RCs associated with high luminosity spirals.

This evidence could be interpreted as a consequence of the self-similarity of dark halos in spiral galaxies. The *differences in shape* of RC, which are evident when we

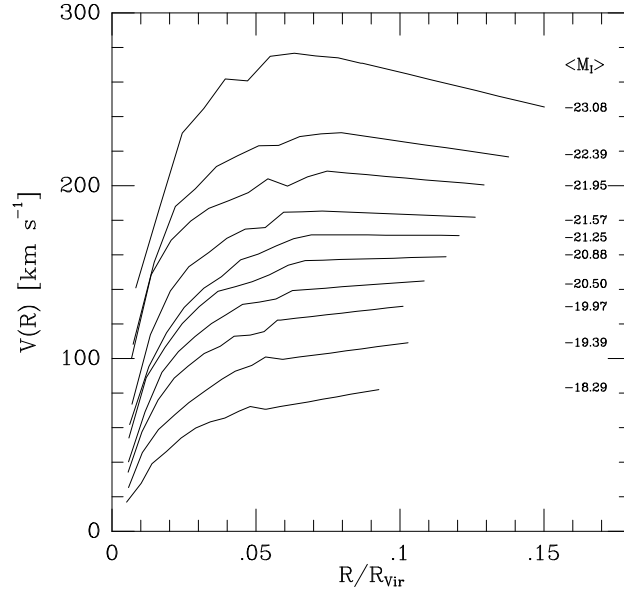


Figure 5: Synthetic rotation curves resulting from the coaddition of the 616 RC's from PS95. Galactocentric radii are normalized to the virial radius

frame them on the visible matter length-scale depends on the fact that doing so we compare *different parts* of dark halos. In fact, while dark halos are self-similar, their interplay with the visible matter is luminosity-dependent. Finally, in Goldsmith et al, we have compared Cold Dark Matter simulated halos with the above RC's (see Fig. 4) and have demonstrated that CDM halos reach their asymptotical velocity too quickly. This is particularly evident in low luminosity RCs which being halo dominated, should better reproduce the halo RC.

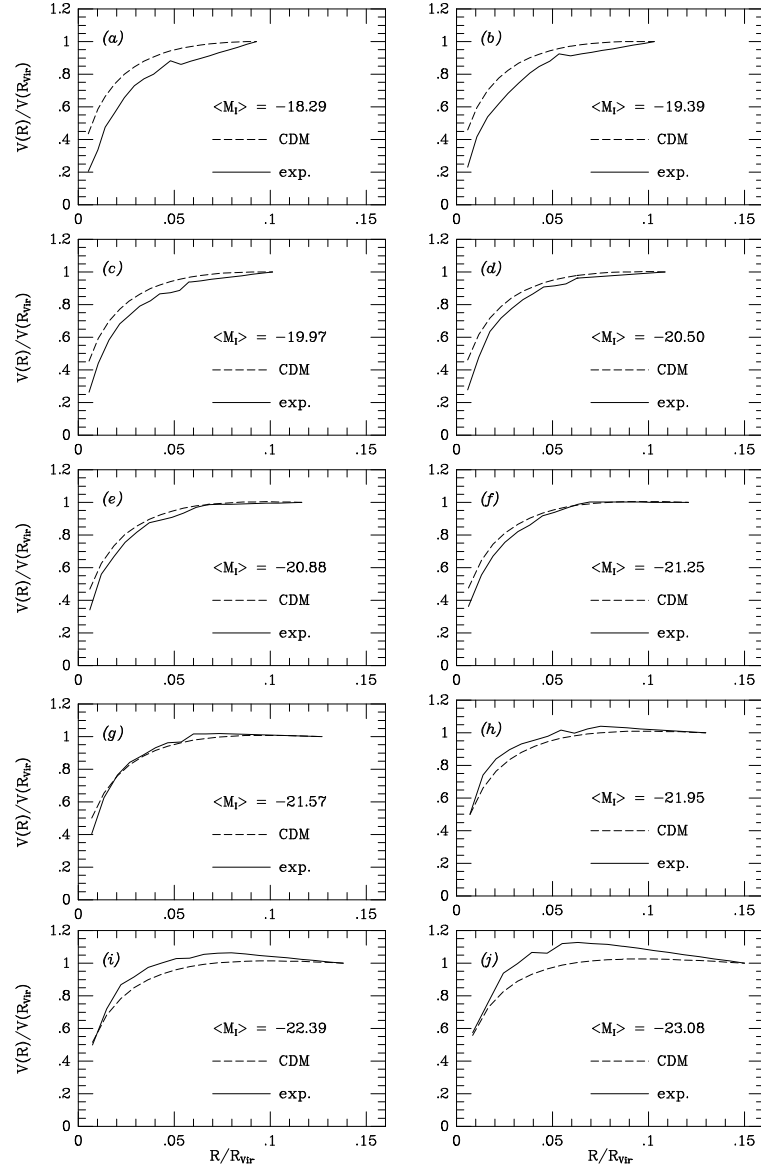


Figure 4: Comparison between the synthetic rotation curves and CDM predictions

5. References

1. Ashman, K. 1992, PASP, 104, 1109
2. Broeils, A.B. 1992, Ph.D. thesis, University of Groningen
3. Casertano, S., & van Gorkom, J.H. 1991, AJ, 101, 1231
4. Cen, R., & Ostriker, J.P. 1993, ApJ, 417, 415
5. Evrard, A.E., Summers, F.J., & Davis, M. 1994, ApJ, 422, 11
6. Fall, S.M., & Efstathiou, G. 1980, MNRAS, 193, 189
7. Goldsmith, O., Persic, M., Salucci, P., & Stel, F. 1995 MNRAS submitted
8. Mathewson, D.S., Ford, V.L., & Buchhorn, M. 1992, ApJS, 81, 413 (MFB)
9. Navarro, J.F., & White, S.D.M. 1994, MNRAS, 267, 401
10. Persic, M., & Salucci, P. 1988, MNRAS, 234, 131
11. Persic, M., & Salucci, P. 1990, MNRAS, 245, 577
12. Persic, M., & Salucci, P. 1991, ApJ, 360, 68
13. Persic, M., & Salucci, P. 1995, ApJS, in press (PS95)
14. Persic, M., Salucci, P., & Stel, F. 1995, submitted
15. Persic, M., Salucci, P., & Stel, F. 1996, in preparation
16. Rubin, V.C., Burstein, D., Ford, Jr., W.K., & Thonnard, N. 1985, ApJ, 289, 81
17. Salucci, P., & Frenk, C.S. 1989, MNRAS, 237, 247
18. Salucci, P., Ashman, K., & Persic, M. 1991, ApJ, 379, 89